

## Submicron sensors of local electric field with single-electron resolution at room temperature

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We describe probes of a local electric field, which are capable of detecting an electric charge as small as the charge of one electron  $e$ , operational under ambient conditions and having a spatial resolution down to 100 nm. The submicron-sized probes were made from a high-density high-mobility two-dimensional electron gas, which is sensitive to the presence of electric charges near its surface. We demonstrate the possibility of using such microprobes for life-science applications by measuring an electric response of individual yeast cells to abrupt changes in their environment. © 2006 American Institute of Physics. [DOI: 10.1063/1.2159564]

Many areas of science and technology would benefit from high-sensitivity local probes of electric field or charge. A variety of such probes that provide a resolution of less than  $e$  have recently been developed for low-temperature applications (typically, for temperatures below 10 K). This includes single-electron-transistor (SET) microscopy,<sup>1</sup> subsurface charge imaging,<sup>2</sup> the use of one-dimensional wires as voltage probes<sup>3–5</sup> and the charge imaging by small field effect transistors (FETs).<sup>6</sup> Extension of the working range of these techniques to room temperature has remained a significant challenge and represents a goal actively pursued by many groups.<sup>7–12</sup> Indeed, sensitive local probes of an electric field operational under ambient conditions could offer a variety of new applications, especially for life sciences (e.g., as an alternative to patch-clamping methods).<sup>13–15</sup> In this letter, we describe a further development of local charge-sensitive techniques, where the important milestone of a single-electron resolution at room temperature has been achieved.

The devices used in our experiments had the Hall cross geometry [Fig. 1(a)] and were made by electron-beam lithography<sup>16</sup> from a GaAs/InGaAs heterostructure with a two-dimensional electron gas (2DEG) embedded at a distance  $d \approx 70$  nm below the surface. The 2DEG contained electrons in concentration  $n \approx 4 \times 10^{16} \text{ m}^{-2}$  and with mobility of  $\approx 0.8 \text{ m}^2 \text{ V s}$  at 300 K. We have studied Hall crosses with the width  $w$  between  $0.3 \mu\text{m}$  and  $3 \mu\text{m}$ . The use of a high concentration 2DEG in conjunction with its high mobility was found to be important for achieving the single-electron resolution, as this ensured a low level of intrinsic noise.<sup>16</sup>

The basic principle of operation of the devices as charge-sensitive detectors is as follows. If a charged object is placed on top of such a cross above its sensitive central area, screening of the charge by nearby electrons leads to changes in a

local concentration in the 2DEG. These changes, in turn, result in conductance changes, which can be detected by standard lock-in techniques. Note that GaAlAs heterostructures have a highly insulating top layer, so that there is no direct electric contact between the studied object and detector and the only interaction between the two is electrostatic.

The spatial resolution of such sensors is determined by their size. The best resolution is achieved when all information about changes in conductance is collected locally from the central area  $w \times w$  in size (Fig. 1). This can be done by

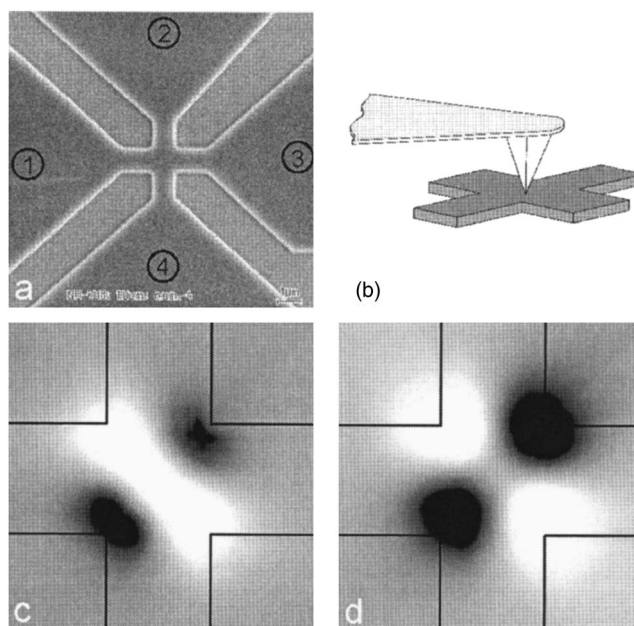


FIG. 1. (a) Micrograph of one of our devices with width  $w \approx 1 \mu\text{m}$ . (b) Basic setup used in our studies. (c and d) Spatial response to a charge placed at an AFM tip in the bend and Hall resistance geometry, respectively. Bright areas correspond to a decrease in resistance and dark areas to its increase for a positive charge at the tip. Thick black lines indicate the Hall cross' edges.

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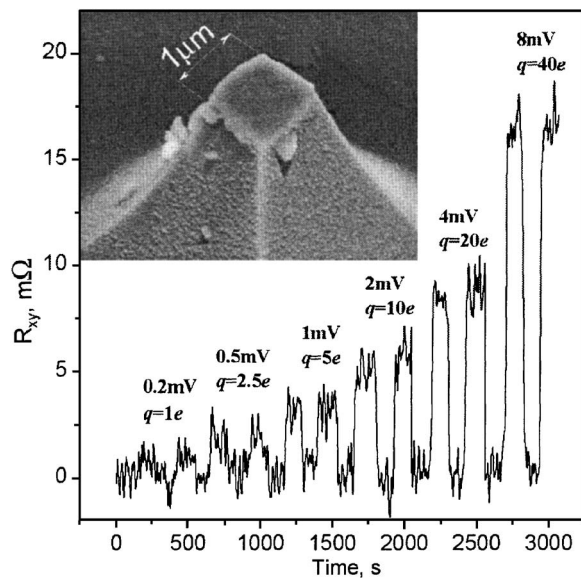


FIG. 2. Changes in resistance induced by voltage applied to the AFM tip shown in the inset. Here, we used the Hall geometry and the tip was placed above one of the corners ( $w \approx 2 \mu\text{m}$ ). Numbers above the peaks indicate  $V$  and the corresponding charge  $q$  at the flat surface of the tip. For each value, the voltage was applied twice for 2 min with a 2 min interval in between. Inset: SEM micrograph of the flat-ended AFM tip used in these experiments.

using two measurement geometries. In one of them (Hall geometry), an electric current is passed through the opposite contacts of the cross [e.g., Contacts 1 and 3 in Fig. 1(a)] while voltage is measured between the other two (2 and 4). In the alternative (bend) geometry, the current is flowing between two adjacent contacts (e.g., Contacts 1 and 2) and the voltage drop is detected across the other pair (3 and 4).

To determine the spatial resolution in the two geometries, we scanned a charged tip of an atomic force microscope (AFM) above the devices [Fig. 1(b)] and simultaneously recorded changes in their resistance.<sup>6</sup> The charge on the tip was controlled by applying (gate) voltage between the tip and 2DEG. Figures 1(c) and 1(d) map changes in the local resistance as a function of the tip's position. In the bend geometry, changes were largest when the tip was above the diagonal separating the current contacts. The situation for the Hall geometry was somewhat more complicated, because the resistance changed its sign as the tip scanned over the cross [Fig. 1(d)]. When averaged over the central area, the measured signal was zero, as expected from symmetry considerations. Hence, the Hall geometry cannot be used for measurements of electric fields created by objects larger than  $w$ . On the other hand, if a studied object is small and placed at one of the corners, the detected signal is of the same magnitude as for the bend geometry. This feature can be used to increase the spatial resolution. To this end, we covered three quadrants of a Hall cross by a layer of an electron-beam resist, leaving one quadrant open. Only when a charged tip was above the open area, a notable response was detected. Importantly, as noise generally increases with decreasing  $w$ , the approach allowed us to improve the spatial resolution to  $< w/2$ , without decreasing a signal-to-noise ratio. Our smallest devices ( $w \approx 0.3 \mu\text{m}$ ) allowed the resolution of  $\approx 100 \text{ nm}$ .

To quantify the charge sensitivity, we fabricated a special AFM tip with a flat end of size  $S = 1 \mu\text{m} \times 1 \mu\text{m}$  (Fig. 2). The flat-tip geometry provides a well-defined capacitive

coupling  $C$  with the 2DEG and therefore allows straightforward calculations of the charge  $q = CV$  at the end of the tip for a given  $V$ . The capacitance was measured experimentally and given by  $C = \epsilon_0 \epsilon S / (d + \epsilon h)$ , and  $\epsilon \approx 13$  and  $\epsilon_0$  are the permittivity of GaAs and free space, respectively. To avoid any mechanical damage, the tip was not in direct contact with the probe but placed at a small distance  $h \approx 10 \text{ nm}$  above the GaAs surface. The distance was controlled by using the AFM force mode. Figure 2 shows an example of the resistive response to different  $V$ . One can see that  $V$  as small as  $0.2 \text{ mV}$  could be detected, which corresponds to charge  $q \approx 1e$  located on the flat area of the AFM tip (signal-to-noise ratio  $\approx 1$ ). For the integration time of  $1 \text{ s}$  in our experiments, this yields a charge resolution of  $\approx 1e \text{ Hz}^{1/2}$  at low frequencies. The resolution decreased by a factor of 3 for our smallest probes ( $\approx 0.3 \mu\text{m}$ ).

It is instructive to compare our devices with SET renowned for their exceptional charge sensitivity. Indeed, in several recent experiments,<sup>7,8</sup> SET with a size of a central island of  $\approx 10 \text{ nm}$  were shown to be operational at  $300 \text{ K}$  and have a sensitivity better than  $\approx 0.1e \text{ Hz}^{1/2}$ . However, the latter is attributed to an *internal* charge that is placed directly on the central nm-sized island. It requires typically  $\approx 0.1 \text{ V}$  on an extended gate (large  $C$ ) in order to change a SET resistance significantly.<sup>7</sup> Sensitivity to electric fields on the level of  $\approx 1 \text{ mV}$  or to *external* charges  $\approx e$  has not been demonstrated for room-temperature SET. Moreover, because the central island is normally embedded well below the surface and strongly screened by nearby source and drain contacts, it will be a challenge to translate the basic sensitivity of room-temperature SET to their sensitivity with respect to external charges.

Finally, to demonstrate possible life-science applications, we have used the technique to detect bioelectrical activity of individual living cells. From the viewpoint of physics, life can essentially be seen as motion of charges, and one can expect that living cells generate local fields due to the motion of ions required for biological functioning. We chose to study yeast cells and fabricated multisensor devices shown in Fig. 3. The size of an individual yeast cell is  $\approx 5 \mu\text{m}$  and the employed geometry allowed comparison between signals from a cell placed at one of the sensors (Fig. 3) with signals from the other crosses used for abiotic control. The measurements were carried out in the standard nutrient medium at  $300 \text{ K}$  (contact regions with open metallization were specially insulated). A drop of a yeast culture was placed on top of the probe, after which a single cell was positioned at one of the crosses using a micromanipulator.

Because water between the cell and the 2DEG probe provided strong electric screening, we minimized this separation by first drying the prepared samples in air. During this procedure, cells became attached to the surface, which was observed as their strong adhesion to particular positions on the device. The yeast cells were not damaged by drying and exhibited consecutive growth after immersing them in a nutrient medium. Despite many experiments, no signal was detected from normally growing yeast cells, even with single-electron resolution. We attribute this to their low activity at the timescale of  $\approx 1$  to  $100 \text{ s}$  accessible in our experiments.

Following the approach demonstrated in Ref. 14, where electric signals from neurons were detected after stimulating them with an electric current, we also tried stimulating yeast cells. This was done by adding ethanol to the nutrient, which

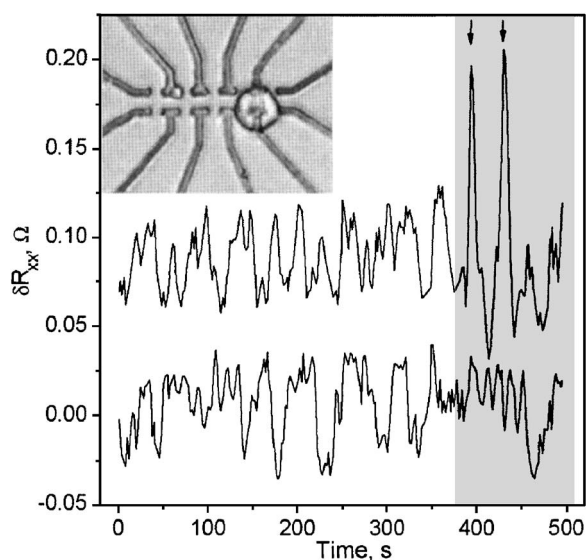


FIG. 3. Inset: Optical-microscope photo of a multisensor device with a live yeast cell attached to the sensor on the right. The scale is given by a distance of  $5 \mu\text{m}$  between adjacent crosses. The main panel shows time-dependent behavior of the bend resistance for one of the reference crosses (lower curve) and for the cross with the yeast cell on top (upper curve), measured simultaneously. A constant background  $\approx 980 \Omega$  is subtracted from both curves. The noise level was  $\approx 50 \text{ m}\Omega$ . No electric signal could be found above noise under normal growth conditions. The shaded area indicates the time when ethanol was added. Two peaks marked by arrows are seen for the cross with the yeast cell attached.

disrupted the membrane functioning. As seen in Fig. 3, yeast cells typically reacted to the changes in chemical environment by producing several distinct peaks corresponding to ejection of negative ions, which were detected by our sensors well above the noise level. Assuming the ions ejected somewhere close to the sensor's surface, the amplitude of the observed peaks corresponds to  $\approx 10e$ . No correlated signal was detected at any of the reference sensors. We attribute the observed signals to a transient imbalance in ion concentrations around the cell as a result of the distraction of its membrane's functioning.

With reference to life-science applications, the presented approach should be compared with the existing FET techniques.<sup>13–15</sup> In the latter case, relatively large Si-FET devices with an active area of  $\approx 100 \mu\text{m}^2$  were used which allowed one to avoid excess noise characteristic to mesoscopic devices and maintain sensitivity to changes in gate

voltage  $\delta V$  on the level  $\approx 0.1$  to  $1 \text{ mV}$ . The above dimensions result in  $C \approx 0.1$  to  $1 \text{ pF}$ , which corresponds to the charge resolution of  $\approx 10^2$  to  $10^4$  electrons. On the contrary, our devices are optimized for the local charge detection. While capable of detecting  $\delta V$  on the same level of  $0.1 \text{ mV}$ , our approach provides two orders better sensitivity with respect to an external charge and, at the same time, collects information from submicron area.

In conclusion, our work demonstrates the possibility of detection of external charges at the level of one electron at room temperature and in biological solutions. Submicron sensors made from a high-mobility high-concentration 2DEG can also be used for scanning probe microscopy, providing a deep-submicron resolution for imaging of local electric fields and charges. The detected response from individual yeast cells indicates the technique's potential for life-science applications.

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